Parameters Affecting the Performance of Residential-Scale Stationary Fuel Cell Systems

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Outline

- Introduction to fuel cells
- Project goals
- Discussion of results from Plug Power Gensys 5c
  - Parametric tests
  - Real-world load simulations
- Discussion of preliminary results from IdaTech EtaGen 5
- Conclusions
- Future work

Benefits of Fuel Cells

- More efficient power generation
  - Direct conversion of chemical energy to electrical
- No rotating machinery
  - Quiet operation
  - More reliable
- No harmful byproducts on hydrogen systems
- Minimal harmful byproducts on reformed systems
  - Almost zero NOx or SOx
  - Very few hydrocarbons
  - No particulate matter
  - Some carbon dioxide

Types of Fuel Cells

- Different technologies
  - Proton exchange membrane fuel cells (PEMFC)
  - Direct methanol fuel cells (DMFC)
  - Phosphoric acid fuel cells (PAFC)
  - Solid oxide fuel cells (SOFC)
  - Molten carbonate fuel cells (MCFC)
- Different fuels
  - Hydrogen
  - Reformed hydrocarbons
    - Natural gas
    - Propane
    - Gasoline

Applications for Fuel Cells

- Portable (~ 10 W)
  - Laptops
  - Digital cameras
- Transportation (~ 100 kW)
  - Drive train
  - Auxiliary power unit
- Stationary
  - Central generation (~1 MW)
  - Large commercial / community generation (~250 kW)
  - **Residential / small commercial (~1-7 kW)**

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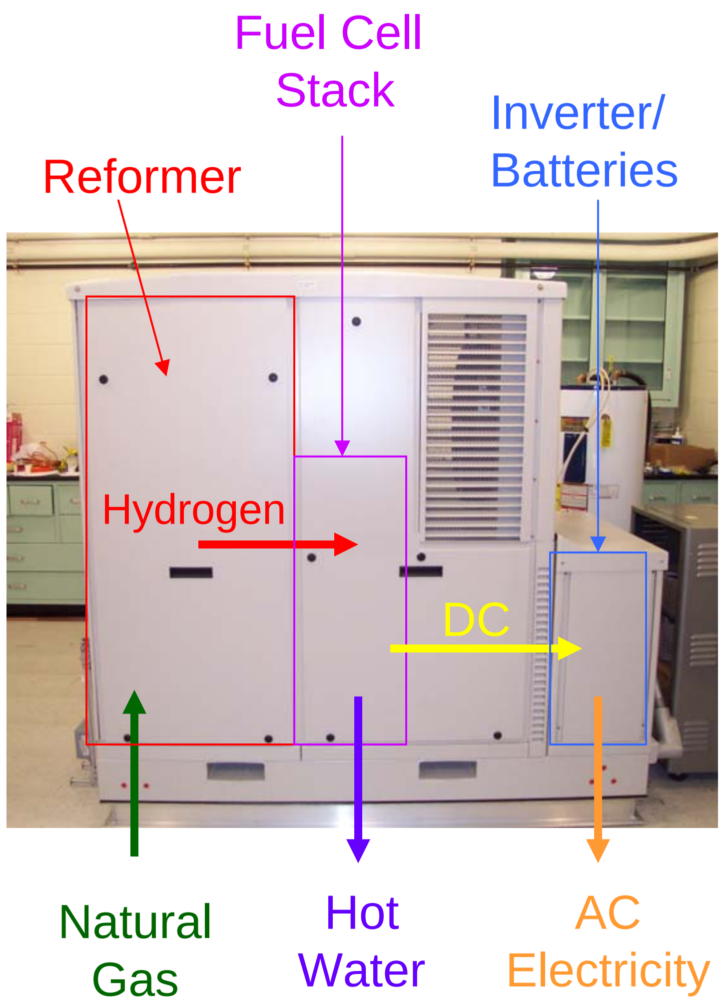
Residential Fuel Cells

- How they work
  - Reformer converts natural gas or propane into hydrogen
  - Fuel cell stack converts hydrogen into electricity and heat
  - Inverter converts electricity from DC to AC
- Benefits
  - Cogeneration
    - Utilize the electrical and waste heat production to maximize efficiency
  - Existing fuel supply
    - Natural gas or propane frequently available at residential and small commercial sites



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Residential Fuel Cells

- Manufacturers
  - Plug Power
  - IdaTech
  - Fuel Cell Technologies
  - Nuvera
  - Proton Energy Systems
  - ReliOn
  - Teledyne


Plug Power Gensys 5c


IdaTech EtaGen5


Fuel Cell Technologies

Proton Exchange Membrane Fuel Cells

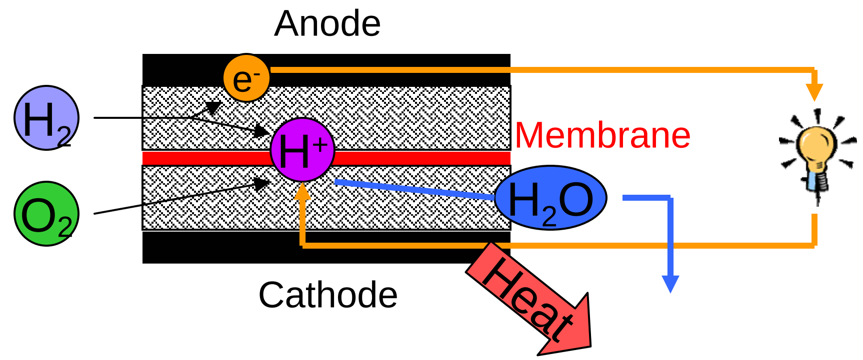
- Electrochemical conversion of hydrogen into electricity
  - Two half-reactions occur on opposite sides of a membrane
- Catalysts at anode separate hydrogen into protons and electrons
- Membrane conducts protons but is not electrically conductive
- Electrons travel through load circuit performing work
- Electrons, protons, and oxygen from air form water at cathode

Anode:

$$2\ H_2 \rightarrow 4\ e^- + 4\ H^+$$

Cathode:

$$2\ O + 4\ e^- + 4\ H^+ = 2\ H_2O + \text{Heat}$$



Future of Residential Fuel Cells

*According to Allied Business Intelligence, Inc., the current $40 million stationary fuel cell market will grow to more than **$10 billion by 2010**.*

- US Fuel Cell Council Website

*According to DOE, "[Proton exchange membrane (PEM) fuel cells] are the **primary candidates for** light-duty vehicles, for **buildings**, and potentially for much smaller applications such as replacements for rechargeable batteries."* *- www.fuelcells.org*

- As fuel cell technology rapidly advances, residential fuel cells will be one of the first applications commercially available
  - Hydrogen or hydrocarbon fuels (natural gas or propane)
  - Backup power, baseline (constant electrical output), thermal load following

- Residential fuel cells are influenced by factors such as:
  - Ambient temperature
  - Electrical load
  - Thermal load (fluid flow rate & temperature)

Problem Facing Residential Fuel Cells

- Current test procedure for fuel cells measures performance at a single rating point (ASME PTC-50)
- **But the real-world performance depends strongly on the residence's thermal load and climate**
- Measured performance of Plug Power system shows that size of thermal load can cut the overall efficiency by more than 50%
- **Therefore, the consumers resulting output could vary significantly for the single rating point value**

Residential Fuel Cell Test Facility Project

Goal: Develop a rating methodology that allows consumers to judge the economic impact of a residential fuel cell system

- Test performance of residential-scale stationary fuel cell systems
- Create empirical performance model
- Draft a rating methodology
- Disseminate results
  - IEA Annex 42 - Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems
  - Fuel cell manufacturers
  - Research community

NIST Residential Fuel Cell Test Facility

- Measurements
  - Fuel energy consumption
  - Electrical energy generation
  - Thermal energy generation
  - Ambient conditions
- Controls
  - Ambient conditions
    - Temperature and humidity
  - Electrical Load
  - Thermal Load
    - Fluid temperature and flow rate
  - Simulated domestic hot water or space heating load

Fuel Energy Subsystem

Thermal Conditioning Loop

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Performance Testing of Residential Fuel Cells

Plug Power Gensys 5c

- **Completed testing of Plug Power Gensys 5c**
- Provides base load electrical power and thermal energy
- 5 kW electrical power
- >9 kW thermal power
- Fueled by natural gas
- Grid-interconnected or grid-independent

Performance Testing of Residential Fuel Cells

Plug Power Gensys 5c Performance Results

- Parameters affecting electrical efficiency
  - Electrical load
  - Degradation over time
- Parameters affecting thermal efficiency
  - Electrical load
  - Ambient temperature
  - Fluid flow rate
  - Fluid inlet temperature
- Transient performance insignificant in context of rating methodology

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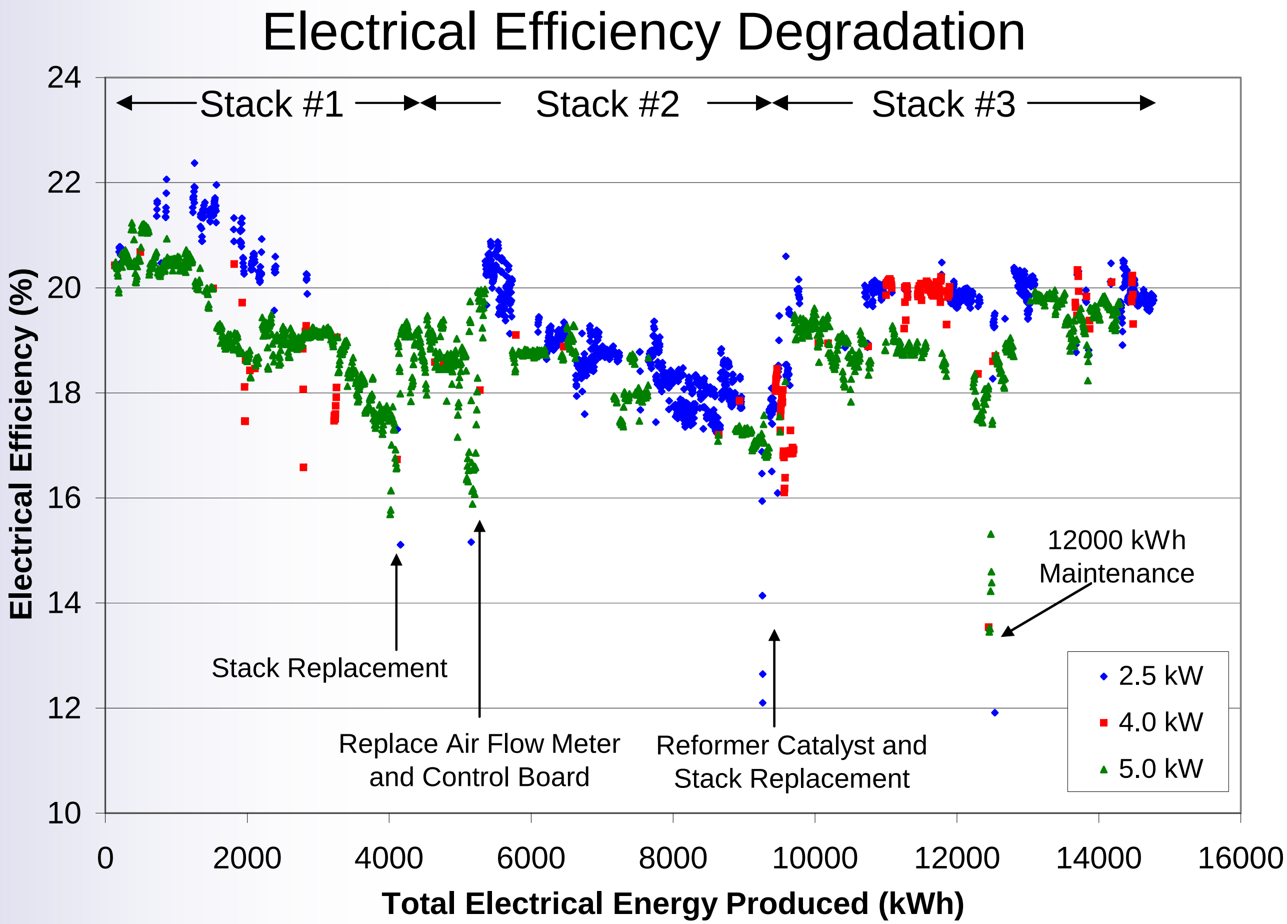
Performance Testing of Residential Fuel Cells



- Sharp decline in efficiency with first two fuel cell stacks made testing difficult
- Replacement of catalyst provided significantly more stable performance

Performance Testing of Residential Fuel Cells

"Bracketing" Test Method

- Original test plan included weekly "baseline" test to quantify degradation, but could not distinguish changes in performance from parameters from changes in performance from degradation

- Developed "bracketing" test method
  - Measure performance at one set of conditions
  - Change a level on a single parameter, and measure steady-state performance
  - Return changed parameter to original level and measure steady-state performance
  - Valid test bracket will have electrical and thermal efficiencies that differ no more than the respective measurement uncertainty

- "Bracket" method ensures that any statistically significant change in performance can be linked to the parameter change

Performance Testing of Residential Fuel Cells

Steady-State Electrical Load Fraction Test

Grid-Interconnected

Electrical Load Fraction (%)	Electrical Efficiency (%)	Measurement Uncertainty (%)	Relative Perform. Index
100	19.4	0.16	
50	20.0	0.17	**1.04**
80	19.8	0.20	**1.03**
100	19.1	0.18	

Grid-Independent

Electrical Load Fraction (%)	Electrical Efficiency (%)	Measurement Uncertainty (%)	Relative Perform. Index
100	18.7	0.17	
50	18.8	0.15	1.01
80	19.5	0.15	**1.04**
100	18.7	0.14	

Performance Testing of Residential Fuel Cells

Thermal Load Parametric Testing

- Steady-state testing to determine the effects of the heat transfer fluid flow rate and inlet temperature
- Set of 10 tests performed at:
  - 2 electrical power levels (50% and 100%)
  - 4 combinations of ambient temperature and relative humidity
  - 80 tests!
- Relative change in performance within bracket calculated

Bracket #	Flow (LPM)	Temp (°C)
	35	55
I	5	55
	35	55
II	35	18
	35	55
	5	18
III	35	18
	5	18
IV	5	55
	5	18

Performance Testing of Residential Fuel Cells

Electrical Efficiency at Various Thermal Loads

Bracket ID	Fluid Flow Rate (LPM)	Fluid Inlet Temp (°C)	Ambient Temperature = 35 °C								Ambient Temperature = 11.5°C							
			RH = 40%				RH = 75%				RH = 55%				RH = 25%			
			LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%	
			η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index	η_e	Index
I	35	55	18.0		20.1		16.8		20.2		18.6		19.5		18.5		19.5	
	5	55	18.1	1.00	20.2	1.00	16.4	0.99	20.1	0.99	18.4	0.99	b		19.0	1.03	b	
	35	55	18.3		20.2		16.4 19.5		20.4		18.4		19.4		18.4		18.3	
II	35	18	18.4	0.99	20.3	1.00	19.2	a	20.4	1.00	18.1	0.99	19.2	0.99	18.7	1.01	18.3	1.01
	35	55	18.8		20.2		17.4		20.2		18.2		19.5		18.7		18.1	
III	5	18	18.7		20.2		18.5		20.7		17.5		19.4		18.4		19.5	
	35	18	18.9	1.00	20.1	1.00	18.6	1.00	20.6	1.00	17.2	0.99	19.6	1.01	18.7	1.01	19.7	a
	5	18	19.1		20.1		18.8		20.7		17.4		19.5		18.5		19.9	
IV	5	55	19.0	1.00	19.9	0.99	17.8	a	20.2	a	17.5	1.02	b		18.3	0.99	b	
	5	18	18.8		20.2		17.0		20.1		17.2		19.8		18.5		19.6	

- Parametric testing showed that none of the parameter changes affected the electrical efficiency
- We can conclude that the electrical efficiency is independent of the thermal load

Performance Testing of Residential Fuel Cells

Thermal Energy Extraction Investigation

Load Fraction (%)	Fluid Flow Rate (LPM)	Fluid Inlet Temperature (°C)	Electrical Efficiency (%)	Thermal Efficency (%)	Overall Efficiency (%)
50	35	55	**19.8**	**19.4**	**39.2**
50	0	0	**19.7**	**0.0**	**19.7**
50	35	55	**19.8**	**19.3**	**39.2**
80	35	55	**20.0**	**28.1**	**48.1**
80	0	0	**20.0**	**0.0**	**20.0**
80	35	55	**20.0**	**28.2**	**48.2**
100	35	55	**18.9**	**32.1**	**51.0**
100	0	0	**19.0**	**0.0**	**19.0**
100	35	55	**19.0**	**32.1**	**51.0**

Extraction of thermal energy has no affect on the electrical efficiency of the system

Performance Testing of Residential Fuel Cells

Thermal Efficiency at Various Thermal Loads

Bracket ID	Fluid Flow Rate (LPM)	Fluid Inlet Temp (°C)	Ambient Temperature = 35 °C								Ambient Temperature = 11.5°C							
			RH = 40%				RH = 75%				RH = 55%				RH = 25%			
			LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%		LF = 100%		LF = 50%	
			η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index	η_{th}	Index
I	35	55	39.2		37.2		36.8		35.9		36.6		28.9		36.8		29.6	
	5	55	10.9	**0.28**	21.5	**0.58**	10.0	**0.28**	21.2	**0.59**	11.5	**0.31**	b		11.6	**0.31**	b	
	35	55	39.6		37.3		36.0 / 39.9		36.4		36.4		28.8		37.1		23.5	
II	35	18	42.9	**1.08**	42.6	**1.15**	45.9	a	43.7	**1.21**	42.3	**1.16**	34.5	**1.22**	41.2	**1.11**	34.6	**1.48**
	35	55	39.7		36.8		37.8		36.0		36.7		27.8		37.1		23.4	
III	5	18	44.5		44.0		45.9		46.1		43.7		35.5		41.4		36.8	
	35	18	43.6	0.98	42.5	0.96	47.9	1.04	44.3	0.97	44.2	1.03	34.0	0.95	40.6	0.98	35.7	a
	5	18	44.8		44.5		46.5		45.6		42.4		35.7		41.6		37.6	
IV	5	55	11.5	**0.26**	21.4	**0.48**	10.8	a	22.1	a	10.9	**0.25**	b		11.2	**0.27**	b	
	5	18	44.8		45.3		45.6		45.5		44.2		37.3		41.8		38.0	

- Thermal efficiency varies between 10% and 48%
- High temperature / low flow rate conditions result in outlet temperature at maximum possible value, which limits the thermal energy available to the consumer

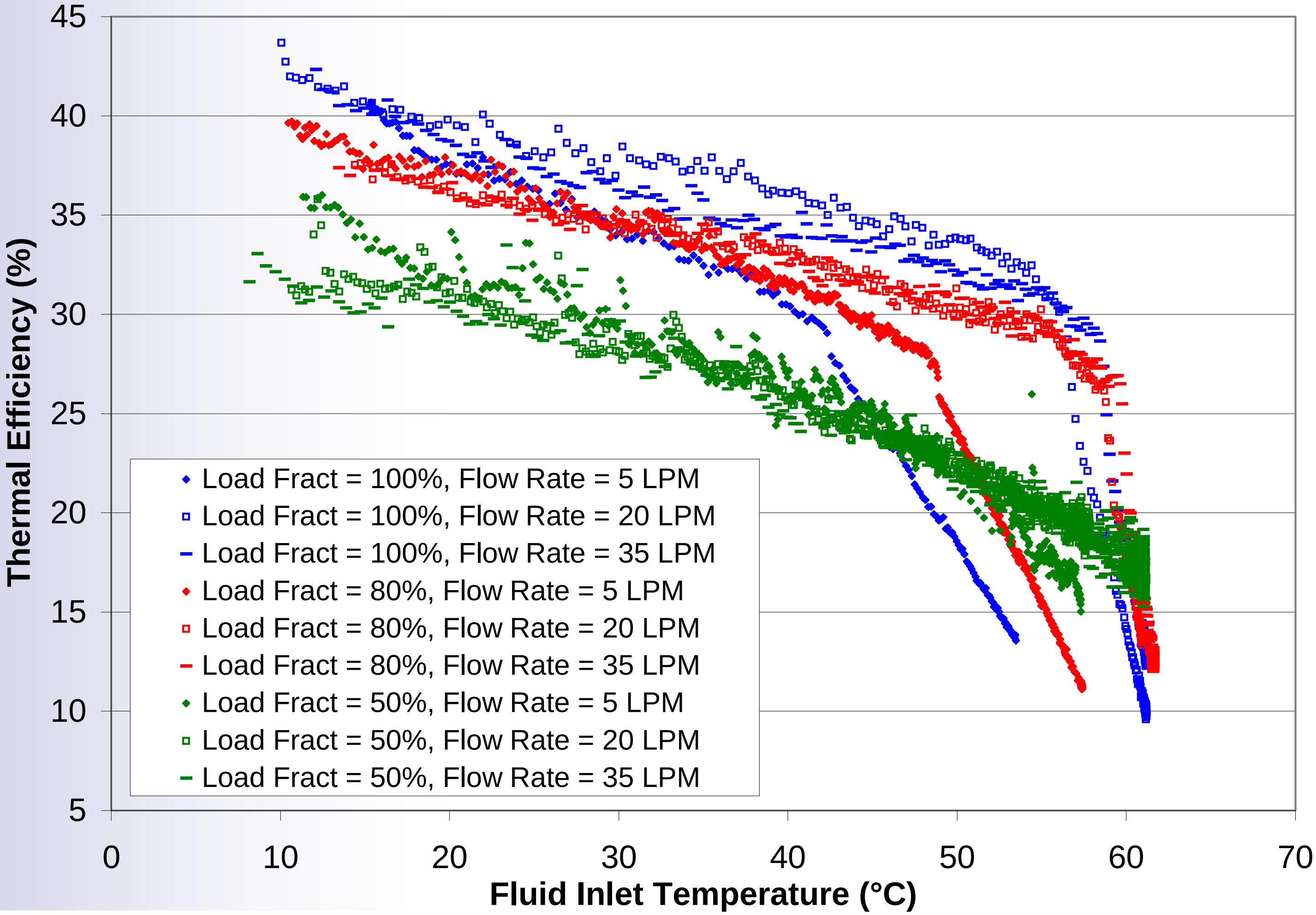
Performance Testing of Residential Fuel Cells

Fluid Temperature Rise Test

- 900+ liters of heat transfer fluid (35% propylene glycol – 65% water) cooled below 18°C
- Fuel cell used to slowly heat fluid, which provides quasi-steady measurement of thermal efficiency versus inlet temperature
- One full test lasts > 18 hours and 10°C step change in fluid reaches steady state in about 5 minutes
  - i.e. test is a valid measure of steady-state thermal performance because the time constant for thermal output is much smaller than the test duration
- Test performed at three flow rates and three electrical power outputs

Performance Testing of Residential Fuel Cells

Fluid Temperature Rise Test



Performance Testing of Residential Fuel Cells

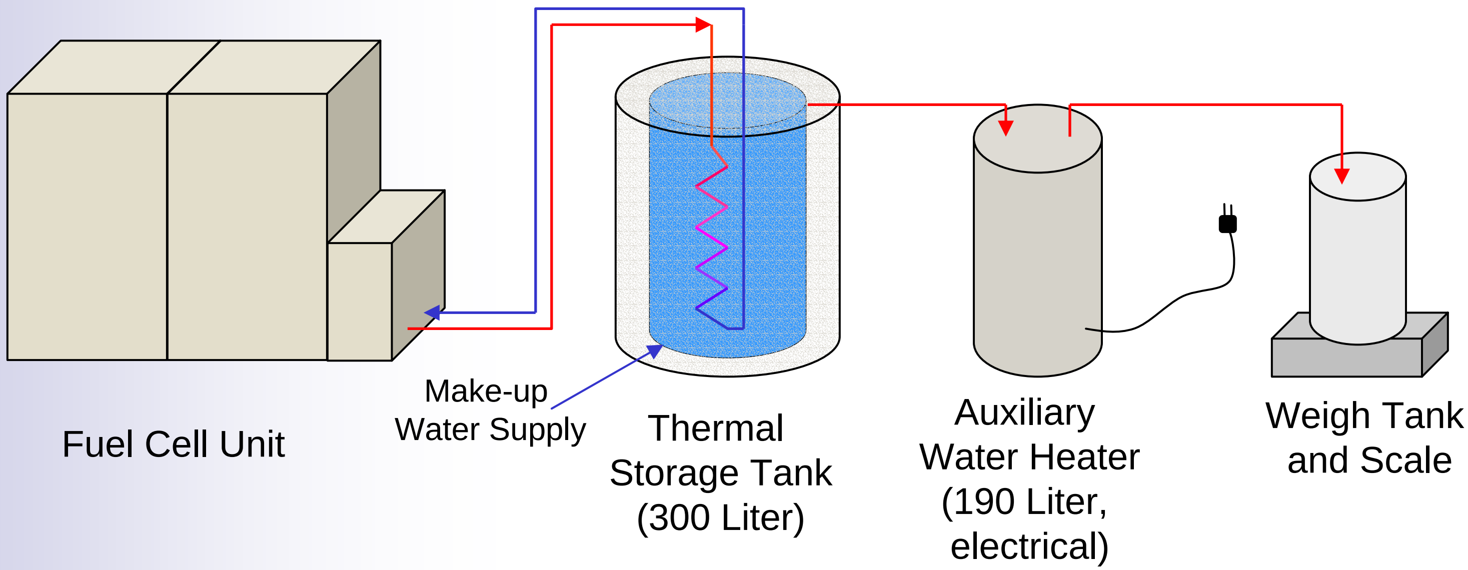
Ambient Condition Tests

Load Fraction (%)	Ambient Temperature (°C)	Ambient RH (%)	Electrical Performance Efficiency (%)	Electrical Performance Relative Index	Thermal Performance Efficiency (%)	Thermal Performance Relative Index
50	35	**40**	**18.1**		**37.0**	
50	35	**75**	**18.3**	1.01	**37.4**	1.02
50	35	**40**	**18.0**		**36.5**	
50	**35**	40	**17.8**		**37.1**	
50	**5**	40	**18.2**	1.01	**26.0**	**0.70**
50	**35**	40	**18.2**		**37.0**	
100	35	**40**	**18.3**		**36.6**	
100	35	**75**	**18.8**	1.01	**36.6**	0.99
100	35	**40**	**18.9**		**37.0**	
100	**35**	40	**18.6**		**36.7**	
100	**5**	40	**18.8**	1.02	**29.9**	**0.82**
100	**35**	40	**18.4**		**36.2**	

- **Ambient temperature strongly affects the thermal efficiency of the system, but not its electrical efficiency**
- Relative humidity has no effect on either the electrical or thermal efficiency

Simulated Domestic Hot Water System

Real-World Thermal Load Simulations



- Domestic hot water simulation: 6 hourly draws of 38 Liters followed by 18 hours without a draw
- Space heating load: draw hourly to satisfy thermal load profile

Performance Testing of Residential Fuel Cells

Real-World Thermal Load Simulations

- Fuel cell used to preheat thermal storage tank (300 liters)
- Thermal storage tank supplies auxiliary electric water heater (190 liters)
- Water drawn from aux. water heater onto scale in weigh tank
- Fuel cell allowed to continue operating after maximum fluid temperature was reached
- Real world simulation data taken at 5 second intervals

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Performance Testing of Residential Fuel Cells

Real-World Thermal Load Simulations

- Domestic hot water load simulated by US DOE water heater test procedure
- Test performed at two electrical power levels and two flow rates
  - Electrical load fraction: 50% and 100%
  - Fluid flow rate: 5 LPM and 28 LPM
- Space heating load derived from DOE2 simulation of “typical” house, which was compiled from US housing and energy use statistics
  - House modeled in Syracuse and Atlanta
  - Peak heating day chosen for space heating load
- Weigh tank system not suitable for larger thermal loads
  - Only one space heating test is valid
  - “Invalid” space heating tests still helpful to model validation efforts

Performance Testing of Residential Fuel Cells

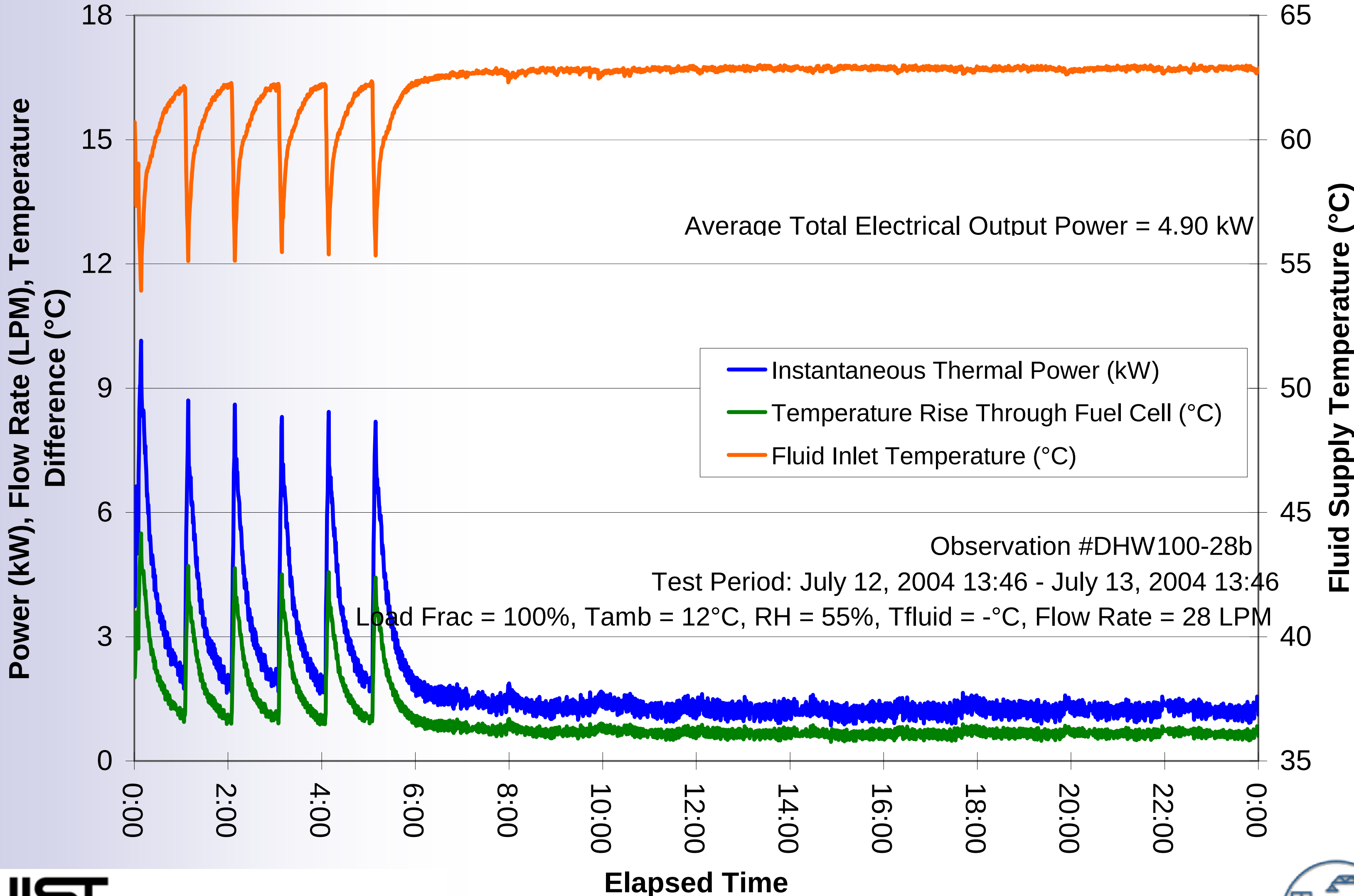
Real-World Thermal Load Simulations

	Domestic Hot Water Load		Space Heating Load
	Load Fraction		
Efficiency	**50 %**	**100 %**	**100 %**
Electrical	18.1	17.2	19.5
Thermal	13.7	6.6	23.6
Overall	31.8	23.8	43.1

- Overall efficiency strongly depends on quantity of thermal load applied to system
- Even space heating load falls short of thermal output capacity of the system, which can achieve overall efficiencies of 68 %

Performance Testing of Residential Fuel Cells

DHW Cogen Temperatures – 100% Load Fraction



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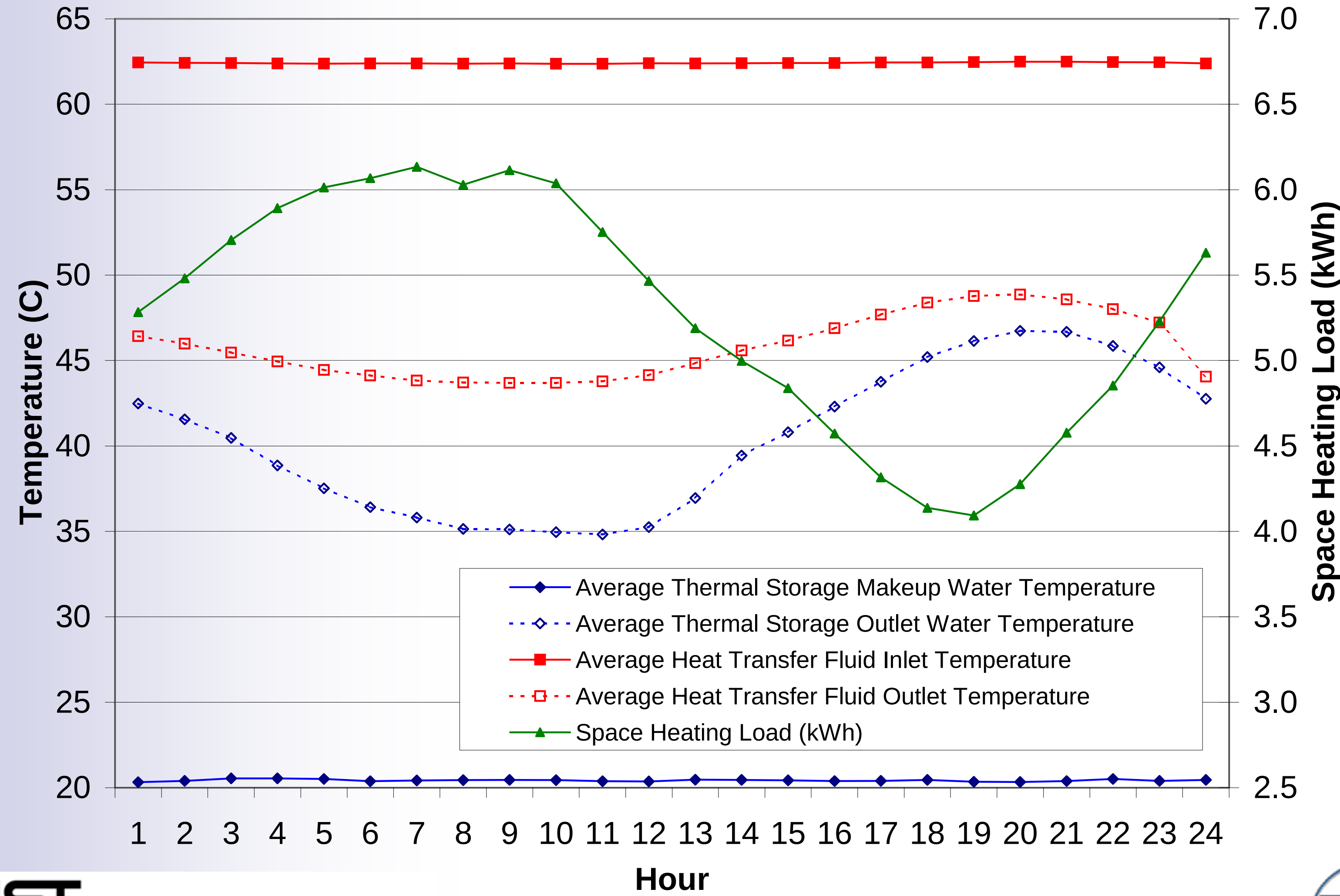
Performance Testing of Residential Fuel Cells

Space Heating Load Performance – 100% Electrical Load in Atlanta



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Performance Testing of Residential Fuel Cells

Electrical Transient Tests

- Description
  - Measured electrical performance during step changes power setting (grid-interconnected) or power output (grid-independent) for all 6 possible permutations
  - Data recorded at 5-second intervals
  - No thermal load extracted to maintain steady conditions
- Results
  - Longest duration between power output levels was 18 minutes, but most were less than 10 minutes
  - Small changes in efficiency during transition measured

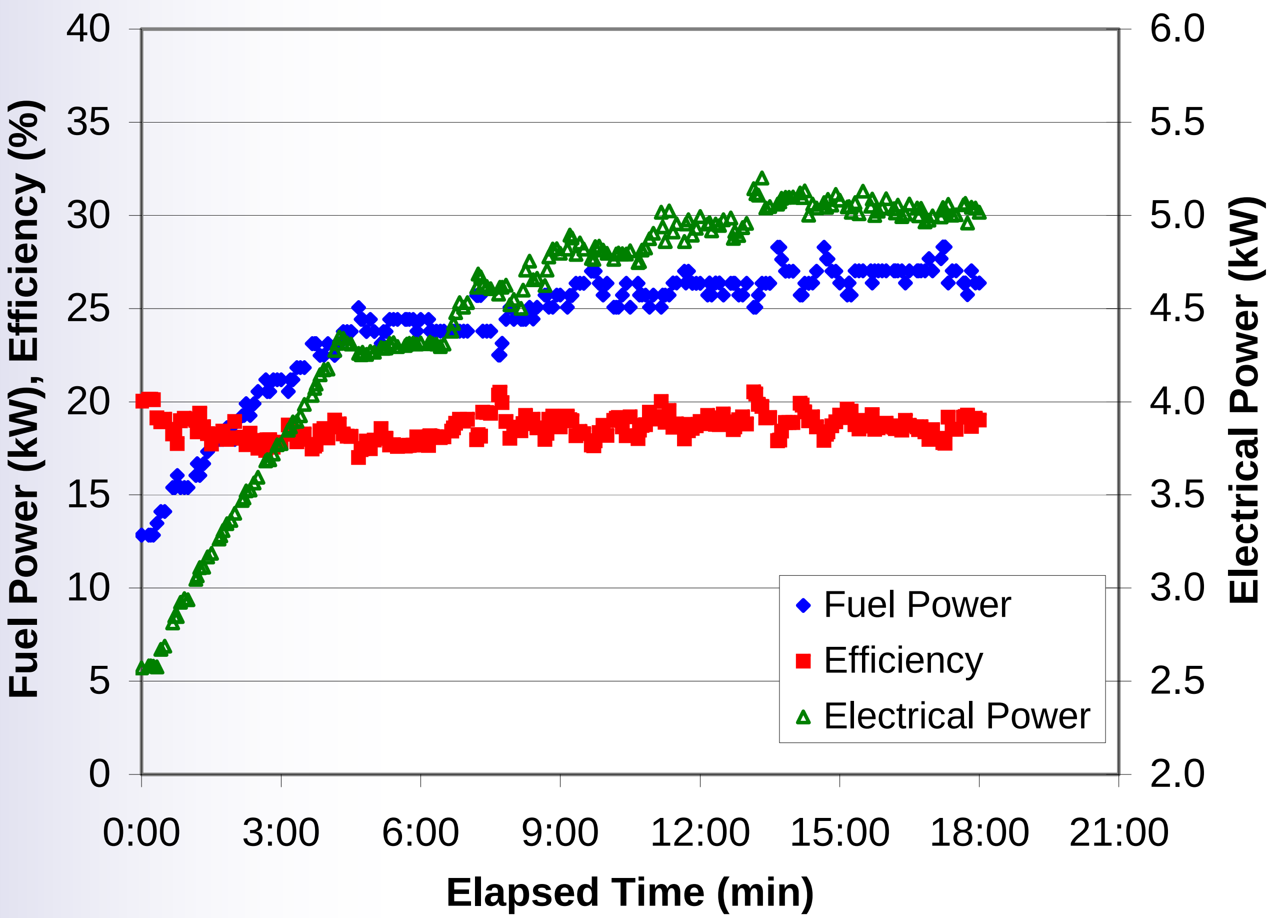
Performance Testing of Residential Fuel Cells

Electrical Transient Tests – Efficiencies before, during and after transition

Steady Electrical Load Fraction	Transition	Grid-Interconnected Electrical Efficiency (%)		Grid-Interconnected Duration (min)	Grid-Independent Electrical Efficiency (%)		Grid-Independent Duration (min)
50		19.4			19.2		
	50 -> 100		18.4	18		20.1	18
100		18.7			18.9		
	100 -> 80		19.5	9		18.8	6
80		19.6			19.8		
	80 -> 50		19.8	8		17.9	6
50		19.8			19.3		
	50 -> 80		19.2	7		20.7	9
80		19.8			19.7		
	80 -> 100		18.7	9		18.9	10
100		19.2			18.8		
	100 -> 50		20.1	18		16.2	7
50		20.2			19.2		

Performance Testing of Residential Fuel Cells

Electrical Transient Tests – 50% to 100% Grid-Interconnected



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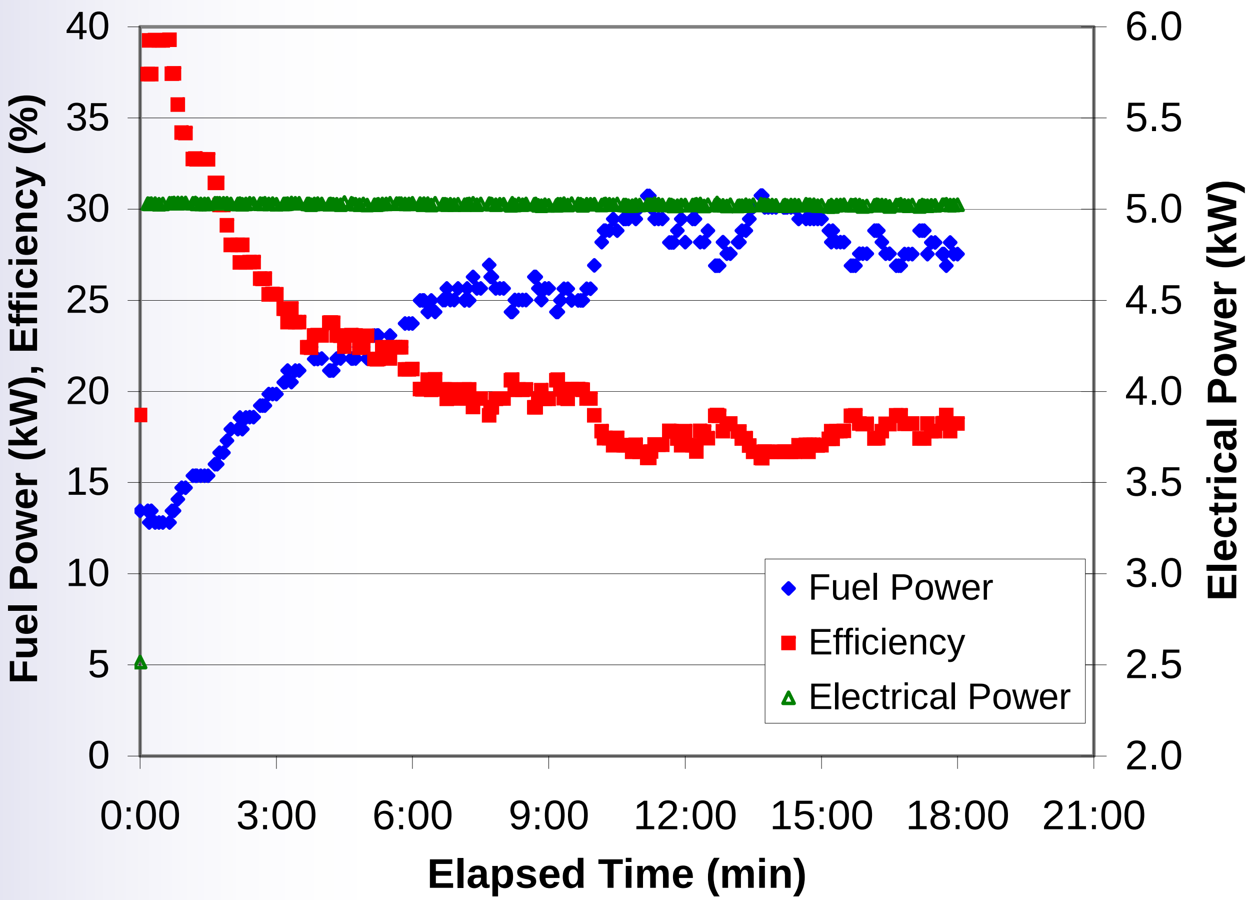
Performance Testing of Residential Fuel Cells

Electrical Transient Tests – 50% to 100% Grid-Independent



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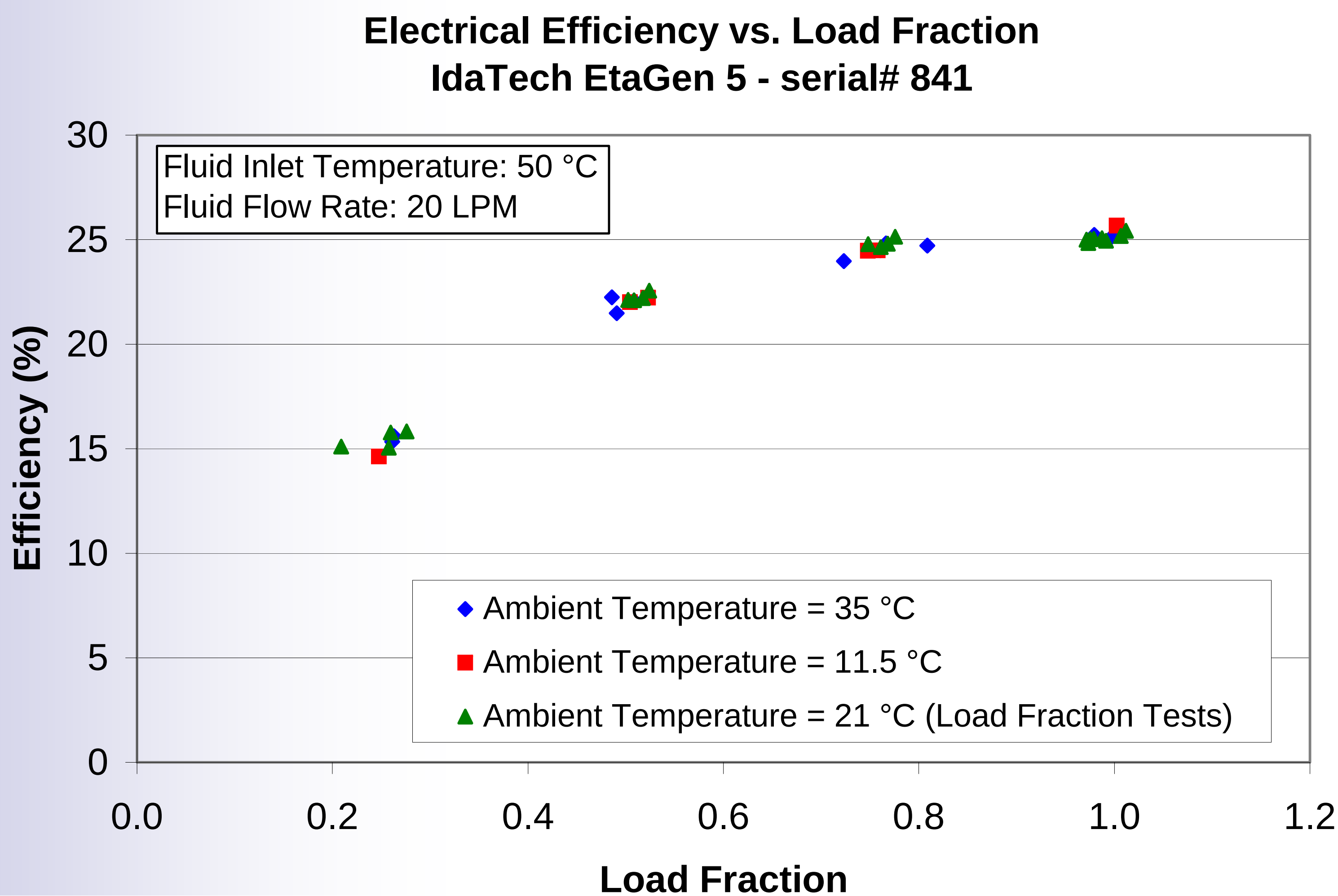
Performance Testing of Residential Fuel Cells

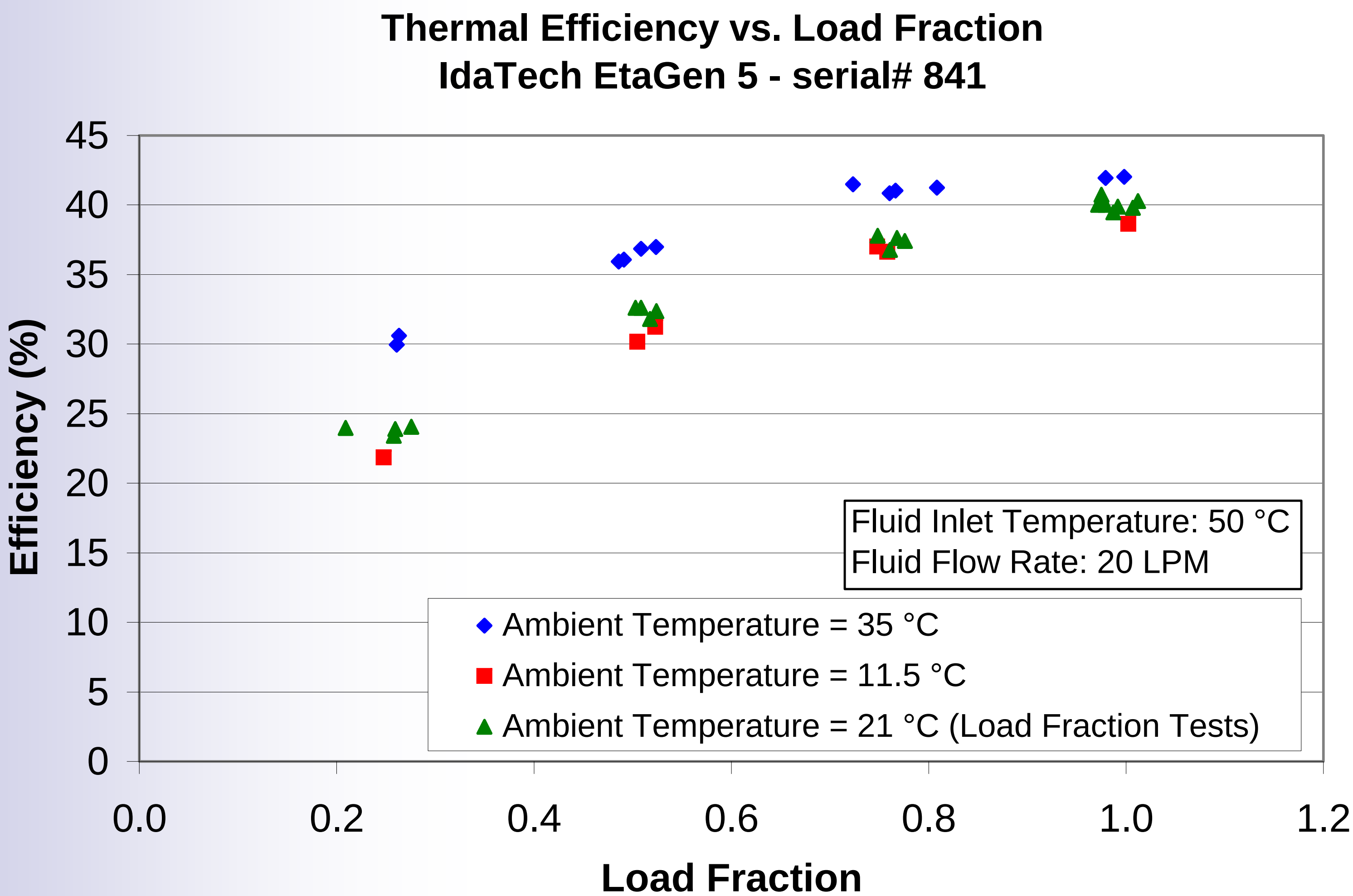
IdaTech EtaGen 5

- **Currently installed in test facility**
- Thermal load-following
  - Electrical and thermal output decreases as fluid temperature rises
- 4.6 kW electrical power
- >8 kW thermal power
- Fueled by natural gas
- Grid-interconnected only

Performance Testing of Residential Fuel Cells



Performance Testing of Residential Fuel Cells



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Conclusions

- **Overall efficiency strongly influenced by quantity of thermal load and ambient temperature**

- **Real-world performance can differ significantly from steady state performance at ideal conditions**

	ASME PTC-50	Space Heating Load	Domestic Hot Water Load
Electrical Efficiency	20.1 %	19.5	17.2 %
Thermal Efficiency	47.9 %	23.6	6.6 %
Overall Efficiency	**68.0 %**	**43.1 %**	**23.8 %**

- **Consumers will need a tool to help judge the economic impact of a residential fuel cell**

Future Work

- Procure, install, and test an additional residential fuel cell with a solid oxide fuel cell
- Develop empirical performance model for systems tested
- Create a draft rating methodology
- Validate rating methodology using empirical performance models
- Submit draft rating methodology to consensus standards organization

Questions?

http://www.bfrl.nist.gov/863/heat_transfer_group/